Low Voltage-High Voltage Distribution for Electronic Apparatus

A discussion of the issue regarding low and high voltage distribution for apparatus used in experiments.

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Voltage/Current requirement at the load

Definition of nominal voltage and maximum and minimum operative voltage. These magnitudes define the output regulation of power supplies and the influence of the distribution system.

Definition of the maximum absolute voltage. This magnitude defines the over-voltage protection to include at the output of the power supply or at the load. Over-voltages can be induced by failures in the power supply, transients due to sudden load changes in the front-end electronics or neighbor systems sharing the cable distribution channels.

Current Requirements / Granularity. The number of channels per 'bias group' is defined by several issues: Number of channel due to integration and size of the sub-detector, integration of LV/HV systems, complexity of the system, space for distribution cables, availability of the system (reliability), practical considerations, etc.

Dynamic current variations. In general, digital electronics can induce sudden changes in current between normal operation and stand-by. These changes induce voltage transients at the output of the power supply and distribution lines that can affect the performance or destroy the front-end electronics.
Short circuit faults between lines or between lines and ground in LV and HV systems can also induce voltage transients in adjacent distribution lines due to magnetic coupling. Limitation of fault currents and reduction of magnetic coupling between conductors in a bundle help to reduce the generation of over-voltage transients.

Location of Power Supplies

High Voltage systems

In general HV power supplies are located in remote areas. It avoids radiation damage on critical components and also allows easy access to the unit for maintenance or repair. As disadvantage power supplies power-up groups of electro-optical devices losing the individual gain adjustment per device.

One of the problems with HV power supplies and their distribution system is the magnitude of the voltage distributed and the stored energy in cables and filters. They can be lethal and also induce high fault currents if no limits are included in the system. Appendix A describes some limitations on the maximum current that HV power supplies have to deliver to avoid shock hazard.

Low Voltage systems

In LV distribution systems the voltage regulation at the load or front-end electronics can be attained by different methods:

a)- Compensation of the cable voltage drop using remote sensing or current sensing.

When this voltage compensation method is used, it is assumed the power supply is located remotely from the load. A remote voltage sensing system closes the loop of the power supply at the load terminals. The filter defined by the distribution cable and by-pass capacitors of the front-end electronics is now included in the dynamics of the power supply. It imposes a bandwidth limit in the power supply to operate stable. In general, this method compensates the steady-state of the voltage drop in the distribution lines but it does not have big effect on the transient behavior. Also, special care must be taken in the selection of the sensing cables and input topology of the remote sensing amplifier. They have to provide good noise rejection because any noise picked by them is translated to the output voltage of the power supply.

Commercial power supplies does not allow more than 0.5-1V of voltage difference between the load terminals and the power supply output terminals. It forces to over-design the section required for cables in long run distributions. Semi-customs power supplies allows higher voltage drops (>1V) in the distribution lines but new problems can appear in very low voltage distributions (2.5V/3.3V) systems. As example, let us consider a LV, high current 2.5V distribution where the voltage drop in the distribution cables is about 1.5V. The power supply delivers 4V at nominal current and the remote sensing adjusts it to 2.5V at the load. For 2.5V electronics we can assume 3.5V over-voltage at the bus can damage it. In this case, sudden current changes can induce at the load over-voltages above 3.5V due to the output of the power supply already is at 4V before the transient starts. Cases like this must be carefully analyzed at the design stage because they can be solved by the inclusion of over-voltage protection at the load, specific design of the power supply with low level of storage energy at the output (low output capacitance), different granularity / cable area, etc.

Other solution in custom power supplies is to ‘feed-forward’ a signal proportional to the voltage drop of the output cables by measuring the output current. This method has the advantage that it is not necessary remote sensing cables and the bandwidth limitations are not so severe. The precision of the remote voltage will depend on the good characterization of the cable impedance used in the calculation of the feed-forward signal.

b)- Local regulation using linear low-voltage drop regulators.

In this case, power supplies without tight regulation can be located remotely and linear regulators can provide the filtering and regulation necessary for the front-end electronics operation. This option allows a bulk LV distribution including local control and individual regulation for a small number of channels. As disadvantage, heat is dissipated in the regulators and has to be removed, which is especially complicated if they are located in central areas of the detector.

c)- Local regulation using DC-DC switching converters.

Using DC-DC switching converters allow distributing higher voltage between the counting room and the detector. This voltage is locally converted to appropriated low voltage and regulated by the switching converter. As advantage this topology distributes high voltage / low current saving costs in cable distribution and allowing to locate the regulator close to the load improving the regulation and transient response. As disadvantage converters have to operate under radiation, they are noisier than linear power supplies, have to dissipate power near the load and can induce instabilities. Appendix B gives some insights about the last issues.

Radiation effects on power converters

Cumulative effects

Total Ionizing Dose (TID): Potentially affects all the components. Commercial components are immunes up to doses of 10-20 Krads. Radiation tolerant devices can reach much higher doses.

Displacement effects: Potentially affects optical devices and bipolar technology devices. Validation test: low energy neutrons.

Single event effects

Single event burnout (SEB): Power Mosfets, IGBTs; *Single event transients (SET), Single event upset (SEU),* Digital ICs *; Single event Latch-up (SEL):* CMOS Tech.

Validation of commercial of the shelf devices (COTS)

Validating COTS becomes a semi-custom design. Commercial devices operates without problems up to 10-20 Krads, displacement effects affect some optical devices at fluences between 10^{11}-10^{12} Neutrons/cm^2. The control electronic circuitry of power supplies are in general built using bipolar technology and can be sensitive to displacement effects if the fluence is higher than 10^{12}Neutrons/cm^2. Low voltage power devices (<150-200V) are resistant to SEB, high voltage power devices has to be de-rated in voltage to perform reliably under high-energy neutrons.

Emitted noise

Noise emitted by power supplies can be separated in radiated and conducted. The first one normally covers a range of frequencies above 30 MHz, while the conducted affects the electronics performance in a range of frequency up to 50 MHz.

Conducted emission

In general, noise can be coupled to the sensitive electronics via conduction through the output cables of the power supplies or via radiation through the input cables. In the last case, the input cables act as efficient antennas for the conducted noise emitted by the power supply inputs. International agencies have defined limits for the input noise conducted emission but there is not official standard for the noise emitted by the output of the power supply (See Appendix B).
As a first approach, power supplies to be installed have to pass International standard for conducted emitted noise at the input and the experiment has to define the noise level accepted for the output. This level depends on the level of filtering used at the front-end electronics, noise immunity of the front-end electronics to common mode and differential mode noise, etc. It is an open question and involves not only the specification of the power supply but also the appropriated design of the front-end electronics to make it immune to common mode currents as example.

Radiated emission

This noise is radiated intrinsically by the power supply. In general it affects the front-end electronics if the power supply is located close to it. There exist International standards for radiated noise and power supplies have to comply with them as minimum requirement.

Harmonics and three/single phase inputs

Single phase / Three phase power supply inputs. Power supplies have to be connected to the AC mains in a coordinated way to balance the power per phase and also to limit the neutral current and harmonics.

Harmonics / Power factor correction: In general linear power supplies have a capacitive rectifier and generate large amount of input current harmonics. It has to be evaluated the impact of this harmonics in the AC system. If the level of harmonics tolerated is lower or equal than the European standard, as example, it forces to uses special input rectifiers included in switched power supplies. In general this special rectifiers include also power factor correction as a feature.

Grounding

Grounding is included in a system for safety purpose. Independently of the grounding topology used by the experiment, as general rules, the electronic equipment designed to be installed in the detector has to verify:

a- GND is only for safety, to minimize shock hazard in case of failure, to define a safe and protected path for fault currents.

b- The electronic system should work without GND connection.

c- GND is not a current return path.

In general the final specification about the grounding connection of both HV and LV power supplies should be coordinated with the overall grounding plan. As common practice, LV power supplies should have isolation transformer such the AC input and the output terminal are electrically isolated for low frequencies. Safety GND and chassis of the power supply have to be connected to the safety GND routed with the input cord.
For HV power supplies the output terminal in general is not floating. To avoid GND loops resistors or zener diodes should be connected between GND and the common of the output terminal.

Appendix A (Notes on High Voltage risks)

This appendix gives some values to take into account during the pre-design or conception of the high voltage system, but it is not conceived as a safety document or policy. This appendix is a summary of 'Safety Analysis of the D0 High Voltage System' by M. Johnson (June 1991)

The shock hazard is only dependent of the current, tests has shown the median sensation for a sample of 167 adult men is about 1.084 mA. At 3 mA there is a mild sensation and at 10mA there is pain but not dangerous. The paralysis threshold starts at 10mA. Ventricular fibrillation occurs for 0.5% of the population if the current is 75mA [1][2].

People can sustain much higher currents for short periods of time. The danger from momentary current pulses is proportional to I^2t, where I is the current and t is the time. Reference [3] indicates the limit I^2t value for a 150 lb (70 Kg) man is 0.027 A^2.sec. Also this reference indicates the human body internal resistance is between 200 and 1000 ohms.

From the numbers and considerations described above, HV power supplies with current limits between 1-3mA should not represent any danger for any person. Additional considerations or additional limits should be considered in case the current limit of the power supply is accidentally disabled.

Charge can be stored in both filter capacitors and distribution cables. Since it will be a pulsed shock, the I^2t associated is:

$$I^2 t = \int_0^\infty \frac{Vo}{R} e^{-t/RC} .dt = \frac{Vo^2 .C}{2.R}$$

where, Vo is the maximum voltage stored, C is the total capacitance and R is the human body resistance. For the minimum resistance, 200 ohms, the limit energy stored should be
5.4 Joules. According to IEC 479-1 [4], the ratio of DC current to its equivalent r.m.s. value of AC having the same probability of inducing ventricular fibrillation is 3.75.
Further information can be found in [5] and [4] and an official reference should be the IEC Publication 479-1.

[1] Dalzier C. "Electric Shock Hazard" IEEE Spectrum Feb, 1972
[2] Lee, R, "Electrical Safety in Industrial Plants" IEEE Spectrum, June 1971
[3] Kleronomos, C; Cantwell E. " A Practical Approach to Establish Effective Grounding for Personal Protection" IEEE conference Record paper, CH460-5/79/0000-49, 1979
[4] http://tis-div.web.cern.ch/tis-div/safdoc/IS/is28/is28_en.html#1.
[5] Fermilab Engineering Standards Manual Chapter 3 (3.2)

Appendix B: Consideration on DC distribution systems based on DC-DC power converters.

DC distribution systems based on DC-DC power converters has the advantage of distributing a relative high voltage and low currents between some remote area and the detector. Voltage is converted-down and regulated locally by the DC-DC switching converters. There are a few disadvantages of this system that have to be taken into consideration during its design.

Constant power load input characteristic of the DC-DC converter:

Switching power converters operating with tight output voltage regulation present at the input a behavior similar to a constant power load. These loads present a dynamical impedance with negative resistance that can destabilize the DC distribution if there is not a proper balance in the power dissipated. The dynamical impedance can be defined as

$$rd = \frac{\partial Vin}{\partial Iin}$$

if we consider the efficiency of the converter is 100%,

$$Pin = Vin.Iin = Pout = Vout.Iout$$

replacing in *rd*,

$$rd = \frac{\partial (Pout / Iin)}{\partial Iin} = -\frac{Pout}{Iin^2} = -\frac{Vin.Iin}{Iin^2} = -\frac{Vin}{Iin}$$

The negative resistance introduces a destabilizing effect in the distribution system. As a simple example we can considerer a DC-DC converter connected to a long distribution line. A simplified equivalent model is depicted in figure B1, *rs* and *Ls* represent the serial resistance and inductance of the line and *Co* is an external filter capacitor connected at the input of the converter. The characteristic equation of this circuit is:

$$l^2 + l.(rs / Ls + 1/ rd.Co) + (rs + rd) / Ls.Co.rd = 0$$

where the factor *1/rd.Co* reduce the system damping or can destabilize it. This factor is attenuated by a large magnitude of both *rd* and *Co*.

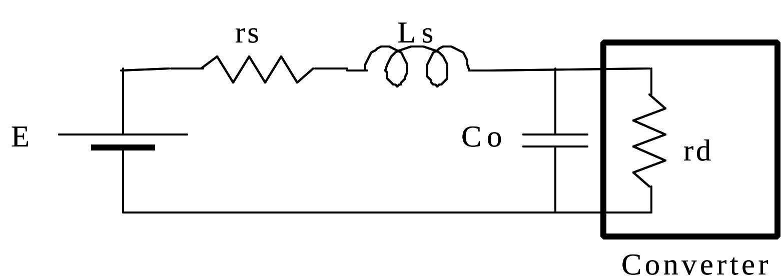

Figure A1: Simplified scheme of a DC distribution system

Radiated and conducted noise

The inherent switching action of power converters produces high frequency noise that is radiated by the converter and conducted through the input and output cables coupling with surrounding systems. There exists a vast collection of standards covering the limits of noise emitted by equipment in industry, military, commerce and residence. In Europe, limits for high frequency interference are specified either by generic standards (EN50081-1 for residential, commercial, and light industry, EN50081-2 for industrial environment) or by standards for specific product families (EN55014 for household appliances, EN55022 for information technology equipment, or EN55011 for radio-frequency equipment) for industrial, medical and scientific applications. In USA, the Federal Communication Commission (FCC) issues electromagnetic compatibility (EMC) standards, with different limits for class A and class B devices. Both FCC standards are defined for digital equipment marketed for use in commerce, industry or business environment (class A) and a residential environment (class B). Typically, European standards for conducted high frequency emissions are specified in the frequency range from 150KHz to 30MHz, and in the United States form 450KHz to 30MHz. The allowed conduction emission levels are between 46 dBuV and 79 dBuV. These limits are imposed to the input cord of the equipment under test and the compliance is verified inserting a line impedance stabilization network (LISN) in series with the unit's AC power cord. The measured values correspond to the voltage level registered across any input wire when it is terminated at the source by 50 ohms impedance to ground (LISN termination). The standards do not distinguish between common mode and differential mode coupling mechanism. Military standards for conducted emissions (MIL-STD-461 CE-03) differ from the other standards. It does not use the LISN, it directly measures the emission current using a current probe. Also it specifies that conducted emissions have to be measured on other cables in addition to the power cord. The range of frequencies covered is between 14 KHz and 50 MHz and the emission level are between 86dBuA and 20dBuA [1]. To compare these standards we should normalize the measurement to dBuA or dBuV assuming a normalized impedance of 50 ohms. Figure B2 compares three standards normalized in dBuV.

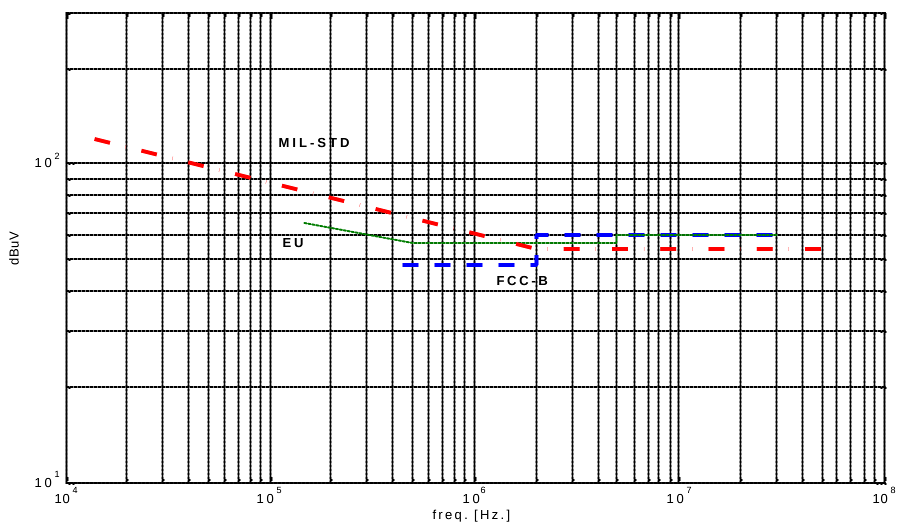

Figure B-2: Conductive EMI standards [Normalized to 50 ohms]